The use of measured and analytical impact data in the design of kinetic energy penetrators

S.T. Burnage & B.R. Waine

Hunting Engineering Ltd., Reddings Wood, Ampthill MK45 2HD, Bedfordshire, UK

ABSTRACT

The work presented in this paper has centred on an extensive measurement programme aimed at identifying the response characteristics of projectiles during penetration of different target types, over a range of velocities and orientations. This experimental work has been supported by analytical studies using a range of methodologies intended to allow identified characteristics to be 'transported' to other designs and conditions. Penetrator responses have been measured using small solid state recorders. Subsequent data processing has included statistical assessment of measured responses using moving-window techniques and the effects of differing constraint regimes operating during penetration and perforation on penetrator dynamic response characteristics.

INTRODUCTION

In recent years, there has been a renewed interest in the use of air launched kinetic energy penetrators as a means of attacking heavily protected static targets. Hunting Engineering Ltd. has undertaken a series of inter-related work programmes aimed at developing compact instrumented penetrators which can defeat such targets. The data acquired from the trials programmes being used in the development of fuzing systems capable of identifying the onset of target perforation.

The study initially concentrated upon the design and development of a general purpose projectile capable of penetrating a range of target types. The penetrator had to also offer full protection to its payload. In this instance, it was the solid state recorder, battery and sensor.

Parametric computer models were used to investigate the interaction of different penetrator designs with a range of target configurations. The compact penetrator selected for the trials programme was based upon the results of this iterative modelling study.
A series of penetration trials were performed at the Hunting Engineering air gun test facility using instrumented penetrators to obtain acceleration signatures against a range of single and multiple targets.

An important feature of the study was the examination of the effects on the captured penetration/perforation signal to variations in sensor location within the projectile. Combining these data with the results from modal tests and modelling enabled the affects of data transportation to be addressed. The ability to predict sensor responses at any given location along the body of the penetrator were investigated.

The analysis of the recorded acceleration data, both in the time and frequency domain, identified signature components which were dominated by the effects of impact excitation and penetrator structural response. Quantifiable trends due to variations in target types and penetrator impact speeds were also observed with the potential for being used as a basis for the derivation of fuzing algorithms.

PENETRATOR ANALYSIS

The penetration analysis method employed in this study was based upon parametric models of the target-penetrator interaction. The requirement to investigate a large number of conditions, representing differing target characteristics and optimisation of penetrator design precluded the use of high order modelling methods - such as hydrocodes. The selected techniques provided an efficient and cost-effective approach, which matched the initial study requirements to design and test a simple compact penetrator.

Initial studies considered the use of semi-empirical codes based upon the SANDIA equations [1] derived by Young in 1972. These equations are based on data obtained from over 500 full scale penetration tests into a variety of targets, including rock, ice, sand and saturated clays. The penetration equations have been derived for two different velocity regimes.

\[
P = 6.08.K.S.N.\sqrt{(W/A)}\ln(1+2.15\times10^{-4}V^2) \quad V<61m/s
\]
\[
P = 0.117.K.S.N.\sqrt{(W/A)}(V-30.5) \quad V>61m/s
\]

where:- K=Weight Scaling . S=Soil Constant. N=Nose Coefficient

The accuracy of these equations is strongly dependent upon the accuracy with which the soil constant S can be determined. Within a restricted range, and appropriate choice of parameters, these equations are capable of giving reasonably accurate estimates of penetration and, by differential analysis, insight into rigid body deceleration profiles. A fit to experimental data of ±20% is generally considered a good result.
An additional solution to the penetration event may be derived using an analytical method in which the equation of motion of the penetrator is expressed in terms of soil resistive forces and solved by direct integration for successive time steps using numerical techniques. The target penetration algorithm is based upon soil mechanics equations for end bearing resistance, dynamic shaft adhesion and confining pressure.

The target resisting force is given by:

\[ F = W - q_b A_x - q_s A_s - q_c A_x \]

where

- \( W \) = Weight of penetrator
- \( q_b \) = End bearing resistance
- \( q_s \) = Shaft adhesion (skin friction)
- \( q_c \) = Confining Pressure
- \( A_x \) = cross sectional area of penetrator
- \( A_s \) = surface area of penetrator

The prediction of target penetration using this analytical method has been validated against SANDIA test results [1,2]. Some eighty test results were used to validate the model, covering a wide range of impact velocities, penetrator mass and diameters for differing target types.

Determining penetration from resistive forces is generally more applicable to soil type targets. This is because the method is based upon a Mohr/Coulomb shear failure relationship. However, for this work, it has been applied to harder targets such as rock and concrete. The failure mechanism is obviously different for these mediums but results do give reasonable comparisons with experimental data such as depth of penetration and deceleration/time curves.
Either of the two analytical methods can be combined with a lumped mass model of the penetrator (Figure 1.) which has the appropriate mass, centre of gravity and moment of inertia. The model represents the rigid body behaviour of the penetrator during impact and penetration. Angled impacts can be modelled by specifying initial orientation and velocity vectors, with the penetrator being 'reacted' against the soil/target resistive forces given by the penetration algorithm. Since for angled impacts, the axial penetration, lateral translation and pitch rotation of the penetrator can be large (particularly for impacts into sand/soil overburdens), then a large displacement method is used for the transient dynamic analysis in which the equations of motion are solved by direct integration.

The results give information on the axial and lateral penetration through the target, velocity and deceleration changes, rotation and final attitude, as well as axial and lateral forces acting on the penetrator.

The technique can be used to examine the influence of various parameters on the penetration process including changes in nose shape, stepped diameters and if applicable, the addition of any shock attenuation devices[2]. The temporal distributed forces acting along the penetrator body length can be applied to a more refined Finite Element model of the penetrator to assist in its structural characterisation.

**PENETRATOR DESIGN**

The penetrator used in this series of trials was of conventional design (Figure 2.), and was essentially a hollowed Ø60mm steel rod with a solid forebody and conical nose. The total mass of the penetrator, as fired, was approximately 5kg.

The hollow main section housed the instrumentation, with a single accelerometer either mounted at the rear of the solid nose section (designated 'forward mount'), or in the rear end cap. The forward mount location offered the potential to monitor the effects of the penetration process clearly, with relatively little contamination from the response characteristics of the penetrator. The aft mounted transducer (more practicable for fuzing applications) was expected to be greatly influenced the dynamic response of the penetrator.

![Penetrator and Instrumentation Package](image-url)
The instrumentation package contained either an ENDEVCO 7270A-60k, or the more robust 7270A-200k accelerometer, an interface to the solid state recorder [3] and a potted 12V battery assembly with interface circuitry. The data recorder operated as a cyclic store which held 32kbyte of data.

Following arming of the instrumentation pack during final assembly, the recorder is ready to record on receipt of a 'Trigger 1' signal. Cyclic recording initiated upon first motion of the penetrator. On impacting the target, a 'Trigger 2' sequence is activated which stops the cyclic storage after a further 30kbyte cycle of data acquisition. This triggering sequence is achieved by the use of two diametrically opposed g-switches, which enables both the pre-impact and penetration phases to be captured by the data recorder.

TRIALS CONFIGURATION

An airgun (Figure 3.) was used to accelerate the penetrators up to velocities in the range 200m/s to 270m/s. It comprised of a 450psi air reservoir and a length of Ø165mm aluminium barrel. A nylon sabot was used to support the penetrator in the barrel and this was separated from the penetrator prior to target impact using a sabot-stripping plate. The targets were 750x750mm reinforced concrete slabs with a thickness of 200mm for the single targets and 100-150mm for the multiple targets. After target perforation, the penetrators were retrieved from a sand butt, disassembled and the data recovered from the recorders via a laptop PC.

DATA ANALYSES

Analysis was performed on the measured data in both the time and frequency domains. The identification and quantification of characteristics within the data which may 'flag' the onset of perforation was a primary objective. The identification of any 'unique' characteristic which may originate from either a failure mechanism of the target and/or the dynamic response of the penetrator was of particular interest.
Time Domain.

Data analyses within the time domain yielded information relating to the loading history applied to each target configuration and its associated penetrator. Typical traces from the forward mounted location (Figure 4.) shows a clearly distinguishable high frequency response superimposed upon a much lower 'rigid-body' deceleration profile. The peak amplitude of the rigid body response for this particular range of target configurations was approximately 16000g. The high frequency, high amplitude responses (in the order of 35000g) are produced by a combination of penetrator flexible body modes, penetrator stress wave propagation and external excitations induced by target responses during perforation.

To investigate the 'rigid-body' response of the penetrator, the high frequency content of the data was removed using a low pass 10kHz filter (Figure 4.). Responses other than pure rigid body motions are present on this filtered data. These are a combination of target failure characteristics (ie. front face scabbing and rear face spalling), coupled with at least one flexible body penetrator mode.

To assess data fidelity, unfiltered acceleration time histories were numerically integrated to give both penetrator velocity and displacement time histories (Figure 4.). These compared favourably with high speed film in terms of predicted target perforation times and corresponding exit velocities.

Figure 4. Time Domain Response

The acceleration time histories were also subjected to statistical analyses in an attempt to identify specific events; in particular the effects of target induced
mechanisms and penetrator responses. Moving window techniques involving the computation of 'running' mean, standard deviation, root mean square (rms), and skewness were undertaken for each acceleration time history. This involved the calculation of the statistical moment for the 100 values preceding the data point under consideration. The use of 100 values was selected after some experimentation, and may not be applicable in all cases.

\[
\bar{x}_j = \frac{1}{n} \sum_{j=1}^{n-1} x_j, \quad n=100
\]

\[
\text{rms}(x_i) = \left( \frac{1}{n} \sum_{j=1}^{n-1} (x_j)^2 \right)^{1/2}
\]

\[
\sigma_j = \left( \frac{1}{n-1} \sum_{j=1}^{n-1} (x_j - \bar{x}_j)^2 \right)^{1/2}
\]

\[
\text{skewness} = \frac{1}{n-2} \sum_{j=1}^{n-1} \frac{(x_j - \bar{x}_j)^3}{\sigma_j^3}
\]

The equations of statistical moments are as shown on the left. The mean, rms and standard deviation failed to show any significant advantages in terms of indicating the onset (or termination) of perforation over that demonstrated by the acquired acceleration time histories. However, the coefficient of skewness [4] being an odd-function, is sensitive to both the sense and magnitude of sample deviations from the mean. The high exponent also gives a greater weighting to large deviations. As such, skewness gives a measure of asymmetry of data about the mean. A value of positive skewness indicates that the majority of large deviations are on the positive side of the mean. In practice skewness has the potential to discriminate flexible body penetrator responses from imposed loading. Purely flexible body responses will approach a skewness of zero as the data will contain no large deviations from the mean. Whilst responses following the applied loadings such as rigid body accelerations will indicate high positive values (Figure 5.).

![Figure 5. Computed Skewness Through Target](image)

**Frequency Domain.**

The frequency domain analysis was performed to attempt to identify and track selected modes during penetration and post perforation. As the projectile impacts the target and commences penetration, its boundary conditions change
from free flight to essentially one of a constrained 'cantilever' beam. Conversely, as the projectile perforates, its boundary conditions revert to free flight conditions. It is the potential to identify the effects on penetration of these variations in constraint conditions which justified undertaking analyses of the data in the frequency domain.

A pair of frequency spectra representing the penetration and post perforation phases of a typical event are presented in Figure 6. In this case, frequency resolution is poor (0.5kHz) and consequently, the values highlighted should be used with caution. However, a general change in frequency distribution between the penetration and post perforation can be identified. During penetration the trend is to excite even numbered modes (ie. second bending), whilst post-perforation responses show a migration to odd numbered modes (ie. first bending and first axial).

![Frequency Spectra Penetration/Post-Perforation](image)

**Figure 6. Frequency Spectra Penetration/Post-Perforation**

**DATA TRANSPORTABILITY**

The effects of variations in sensor location within a penetrator on measured and/or predicted acceleration responses was of prime interest within this phase of the study. The objective was to assist fuze designers in the prediction of acceleration environments at any practicable sensor location based upon measurements derived at some other position on a penetrator. In undertaking such data 'transportation', due account must be taken of any future penetrator body design and sensor mounting configuration as determined by its modes of excitation.

The accelerometers attached directly to the fore-section of the penetrator produced acceleration responses that were (as expected) only minimally affected by penetrator characteristics. Consequently, it is likely that small changes in transducer location would have little effect on measured response. Practical operational fuzing requirements will almost certainly call for sensors to be located at the rear of a penetrator.
However, accelerometers mounted at the rear of a penetrator are significantly affected by penetrator dynamic response characteristics. This will imply that measured responses will be greatly affected by small changes in sensor location.

The measured axial response of a front and rear mounted accelerometer impacting and perforating identical multiple targets is shown in Figure 7.

![Figure 7: Effects of Front and Rear Mounted Accelerometers](image)

A significant increase in magnitude and duration of vibratory response following initial impact can be seen for the accelerometer located in the rear endcap. This was particularly prevalent during second target penetration in which an increase in impact angle of obliquity, following first target perforation, exacerbates the rear sensor response.

To investigate the relative distribution in dynamic response of the projectile along its length, a pendulum impact test was performed on a penetrator which contained four accelerometers. Pairs were oriented longitudinally and laterally in the front and rear of the penetrator. A Finite Element model replicating the modal characteristics of the penetrator was then subjected to an identical transient excitation and the predicted responses at corresponding front and rear sensor locations computed. Results from the modal test and model correlated in terms of amplitude - although modal model decay rates were rather poor, indicating that the model damping characteristics required further refinement.

The peak axial and lateral accelerations, as predicted by the model, were extracted at various stations along the length of the penetrator body and then normalised with respect to the forward accelerometer responses. The plot of these distributions (Figure 8.) are a good indication of 'transportation'.

Axial distributions show that the peak responses at the rear of the penetrator are double those experienced at the forward location. A similar magnification is also seen in the lateral orientation. However, the lateral response of the hollow section just forward of the endcap has increased five fold. This is attributed to excitation of the radial (belling) modes of the penetrator.
us by applying either measured or theoretical transient loading conditions to a validated penetrator modal model, a fuze designer can select potential sensor sites from the responses predicted by the model. The influence of mounting the fuzing device at the preferred location on the penetrator could also be adjudged by refining the modal model to include the detail design of the fuze assembly.

![Graph of Predicted Acceleration Amplification Distribution](image)

**Figure 8. Predicted Acceleration Amplification Distribution**

**CONCLUSIONS**

The penetrator performance and structural response characteristics predicted by the pre-trials penetrator analyses were configured against the observed results from the trials programme.

The utility of the instrumentation packaging has been amply demonstrated, despite the onerous restrictions imposed by the penetrator geometry. The devised instrumentation scheme operated with excellent reliability.

Interpreting signature for use in the detection of breaches in protective material yielded promising results. The structural response of the penetrator was shown to rapidly dampen after perforating the target(s). Relatively straight forward signatures obtained during penetration, for both forward and rear mounted accelerometers, indicates that interpretation of signatures from thin targets at this stage can be considered feasible. Relatively sophisticated signature analyses techniques both within the time and frequency domain also have potential. However, their true value, particularly with statistical analyses, may only be apparent for complicated signatures against extended multi-component targets.

Investigations into data transportability, for use by fuze designers, produced a method using validated modal models which accurately predicted acceleration amplitude distributions along the length of the body in both the longitudinal and lateral penetrator axes. This technique will be particularly beneficial in optimising any design of sensor mounting configuration.
ACKNOWLEDGEMENTS

This study was performed on behalf of the Defence Research Agency, Farnborough, assisted by Hunting Engineering Ltd. Private Venture funding, to obtain and analyse signatures for kinetic penetrators striking and perforating concrete targets.

REFERENCES